

Theoretical Summary of Moriond 2004: QCD and Hadronic Interactions

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Theoretical talks and discussions at *Rencontres de Moriond 2004 “QCD and Hadronic Interactions”* are summarized. Following exciting recent experimental discoveries, theoretical developments were reported in the description of heavy ion collisions, light hadron spectroscopy, and the physics of hadrons containing heavy quarks. Some of the predictions have already been tested by subsequent experiments, notably by the very recent SELEX observation of a possible new charm-strange meson $D_{sJ}(2632)$.

1 Introduction

The year between Rencontres de Moriond in 2003 and in 2004 was rich in exciting discoveries challenging some established views on QCD and hadronic interactions: evidence of exotic behavior in heavy ion collisions, sightings of pentaquarks, and new charmed particles, just to name the most publicized ones. Some of these phenomena had been predicted or speculated about by theoreticians, and all fuelled interesting discussions at the QCD Moriond 2004.

In this summary, topics are organized according to increasing “hardness”, or decreasing characteristic distance scale of phenomena. Thus, we start with heavy ion collisions and QCD evolution equations, followed by properties and interactions of light hadrons, and finish with a review of the recent progress in charm spectroscopy and the physics of hadrons containing the b quark.

2 Heavy ion collisions: new phase of QCD?

Experiments at the Relativistic Heavy Ion Collider (RHIC) probe nuclear matter in a new regime of high temperature and density. Heavy ion collisions have been studied extensively in the past, most recently at the Super Proton Synchrotron (SPS) at CERN, where experimenters announced circumstantial evidence for a new state of matter in 2000.

One novel feature of RHIC is that the energy of individual parton collisions is sufficiently higher than at the SPS for jets to be produced and detected. Observation of jets, and their dependence on the colliding particles and the centrality of collisions, probes the state of hadronic matter under extreme conditions.

Particularly striking evidence that something new occurs in the nuclear medium after the collision is seen in the so-called suppression of back-to-back jet correlations, discovered during

the last year and reviewed at this meeting.^{1,2} In the former reference, in Fig. 4 we see a typical configuration of an off-center collision of large nuclei. The right hand side of that Figure shows angular correlations of dijet events.

In the case of proton-proton collision, conservation of momentum forces the two jets to appear back-to-back. This is represented by the two peaks in that figure, separated by 180° .

In collisions of gold-gold nuclei, the overlap region is elongated in the direction perpendicular to the plane of velocities of incoming nuclei (reaction plane). Thus, jets emitted within that plane have a relatively short path to leave the overlap region. Although they still have to cross a region of normal nuclear matter, it does not affect them significantly, and the back-to-back correlation is preserved (a lower peak in the 180° correlation).

The intriguing phenomenon is observed for the “out of plane” jets. When one jet is observed in the direction (roughly) perpendicular to the reaction plane, none is observed in the opposite direction! It seems to get totally absorbed, presumably by interactions with the putative new state of QCD matter that arises in the overlap region.

No similar suppression of the back-to-back jet correlations has been observed in collisions of small projectiles with gold (deuterium-gold).³ This is interpreted as a clear evidence that the suppression is a final-state effect, due to interactions with the post-collision medium, rather than an initial state effect, such as nuclear shadowing.

Explaining the mechanism of the jet attenuation is a challenge for theorists. Various approaches to describing hadron interactions with the medium have been discussed and can be found in these proceedings.^{4,5,6} Other probes of the dense medium include gluon radiation off heavy quarks⁷ and prompt photons.⁸

3 Evolution equations and resummation techniques

Evolution equations are a source of information about physics outside regions where fixed order perturbation theory is appropriate. In this meeting, their applications were seen in several contexts, from the small x limit, to heavy flavor production (see Section 6), to Higgs production in the highest energy collisions.

In the limit of very high center-of-mass energy, \sqrt{s} , the BFKL equation describes effects of large logarithms in the ratio of the (fixed) transferred momentum to \sqrt{s} . This regime is of significant practical interest, for example because gluon exchanges give rise to multi-jet events through the BFKL dynamics, and create a background for the Large Hadron Collider (LHC) searches for new heavy particles, and in studies of known particles such as the top quark.

In the leading order (LO), various techniques are available for solving this equation, thanks to the conformal symmetry of the BFKL kernel. This symmetry is spoiled in the next-to-leading (NLO) order, because of the running coupling constant, and the solution becomes a challenge. Recently, a solution method at the NLO has been found.^{9,10,11} It expresses the solution as a phase space integral, thus controlling the energy-momentum conservation. This is an important breakthrough, clarifying previously found paradoxes in the behavior of the NLO solutions, and opening a way to phenomenological studies of the BFKL dynamics.

As the cross section grows with increasing energy, the BFKL evolution must be supplemented with non-linear effects. The number of partons cannot grow without limit, and a so-called saturation is reached. Near the saturation regime, another equation has been proposed by Kovchegov.^{12,13} At this meeting, recent improvements on this formalism, including effects of fluctuations, were reported.¹⁴

The high energy collisions at the LHC will likely result in production of the Higgs boson. Two mechanisms of the Higgs production were discussed.^{15,16} In the leading production channel, through a gluon fusion, it is important to determine the perturbative QCD corrections to the transverse momentum (q_T) distribution of Higgs bosons. In the majority of events, Higgs will

have a relatively small transverse momentum, $q_T^2 \ll M_H^2$, and the distribution obtained in a fixed order perturbative calculation will be distorted by large logarithms $\ln(M_H^2/q_T^2)$. The state of the art in resumming such effects has been presented.¹⁶ The QCD description includes now next-to-leading order corrections to the distributions, improved by a resummation of next-to-next-to-leading logarithms.¹⁷

4 Light hadrons: real and virtual

4.1 Pentaquarks

Exotic baryons, with a flavor structure more complex than can be built with three quarks, were searched for by a number of experiments, especially in the 1970's, always with negative results. Since no evidence of their existence was found, theoretical models predicting their existence were treated with suspicion. Eventually, the experimental searches were given up, until recently.

Since the last year, we have been witnessing a revolution. First, the pentaquark $\Theta^+(1540)$ was discovered, after a prediction of its mass^{18,19,20} and a narrow width.²⁰ a remarkable success for both theory and experiment. Further, cascade pentaquark states Ξ^{--} and Ξ^0 were reported. Four such particles are expected to form an isospin quartet. The doubly-negative and the neutral ones can decay into final states with all particles charged and are therefore somewhat easier to identify, but even for them the evidence is scarce. In addition, the antiparticle of Θ^+ has been detected by one experiment. Experimental situation is not yet entirely clear: some experiments do not see states that others do, and mass determinations vary. This is summarized in Marek Karliner's contribution.²¹ Lack of confirmation by some experiments may be interpreted as evidence of particular production mechanisms.²²

The nature of the pentaquark states has been vigorously disputed since their reported discovery. It does not seem possible to explain the low mass and narrow width of Θ^+ in the constituent quark model.²³ The mass prediction for a $uudd\bar{s}$ state (the lowest quark flavor content consistent with $\Theta^+(1540)$ decays) is about 1800 MeV. Its width would be expected in the ballpark of 100 MeV, while the experiments suggest one or two orders of magnitude smaller width.

Among the more successful models, the main dividing line is between the chiral soliton and the correlated quark approaches. Other interpretations have also been proposed and some were discussed at this meeting.²⁴ The chiral soliton model addresses the non-trivial structure of the QCD vacuum. Its clear achievement is the prediction of the Θ^+ that led to its discovery. The correlated quark model^{25,26} operates with quasiparticles, constituent quarks. Unlike in the traditional quark model, in this approach quarks are spatially correlated and form diquarks. It has been speculated that the existence of diquarks may help explain hard-core repulsion between nucleons and the $\Delta I = 1/2$ rule.²⁷

Although the two approaches seem to be fundamentally different, they were shown to be equivalent and connected to QCD in the limit of a large number of colors, $N_c \rightarrow \infty$.^{28,29} In fact, it has been argued that the accuracy of either model does not extend beyond where their predictions are the same.²⁸

There is a number of outstanding questions regarding pentaquarks, among which solidifying evidence of their existence is the most important. The production mechanisms, leading to surprisingly large production cross sections, are a very interesting issue. Some information about production mechanisms and wave functions may come from searches in heavy meson decays.³⁰ Determination of parity is often mentioned as very important; the chiral soliton and correlated quark models all predict positive parity. The fact that several well-established baryons, including some ground state cascades, have not had their parities measured yet, shows that this may be a very difficult task.

There is also a tantalizing signal of a charmed pentaquark $\Theta_c(3099)$, significantly heavier

than predictions based on analogies with $\Theta^+(1560)$, on the order of 2700 MeV. Unfortunately, evidence for this state comes from only one experiment (H1). If it is confirmed, there may be a lighter charmed pentaquark of which $\Theta_c(3099)$ is a so-called chiral doubler of opposite parity.³¹ We will return to this topic in Section 5.

4.2 Muon $g - 2$

In January 2004, the Brookhaven $g - 2$ Collaboration announced a measurement of the negative muon anomalous magnetic moment,³²

$$a_{\mu^-} \equiv \frac{g_{\mu^-} - 2}{2} = 116\,592\,140(85) \times 10^{-11}. \quad (1)$$

This is higher than the 2000 measurement with positive muons³³ by 100×10^{-11} . This difference is statistically insignificant and the two values can be combined to give the world average for the muon,

$$a_{\mu} = 116\,592\,080(60) \times 10^{-11}. \quad (2)$$

The upward shift of this average, due to the latest μ^- data, increases the discrepancy between the experiment and the Standard Model prediction. At this meeting, Arkady Vainshtein reviewed recent improvements in the most challenging aspect of the latter, namely the hadronic effects. All types of hadronic contributions to $g - 2$, shown in Fig. 1, have been subjects of interesting

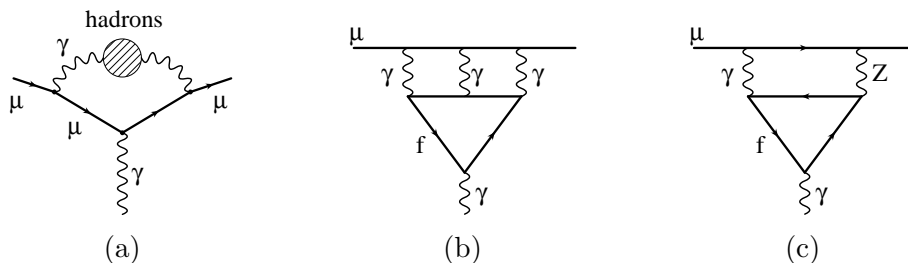


Figure 1: Examples of hadronic contributions to the muon anomalous magnetic moment: (a) vacuum polarization, (b) light-by-light scattering, and (c) hadronic-electroweak contribution. "f" denotes the quark species in the triangle loop.

theoretical disputes and controversies in the last few years. Among them, the light-by-light (LBL) scattering part in Fig. 1(b) may set the ultimate limit for the accuracy of the Standard Model prediction. Thus, its recent study by Melnikov and Vainshtein³⁴ is an important new development.

Previous studies of this contribution were based on assumptions about photon interactions with virtual pions (and other light mesons), extrapolated from known interactions with on-shell pions. That reasoning turns out to be not entirely correct. The improved analysis³⁴ employs the operator product expansion and matching with exactly calculable asymptotic behavior of QCD amplitudes. One finds that contributions of large virtualities of loop momenta are less strongly suppressed than had been previously assumed. As result, the LBL contribution turns out to be larger by about half than its previous estimates, bringing the Standard Model prediction somewhat closer to the Brookhaven experimental result. The theoretical prediction is smaller than the experiment by about $2.2\text{--}3\sigma$, depending on the treatment of the vacuum polarization contribution in Fig. 1(a), obtained from e^+e^- annihilation into hadrons.

The vacuum polarization contribution is responsible for the major part of the present theoretical uncertainty. So far, it has been estimated using $e^+e^- \rightarrow$ hadrons or hadronic decays of τ leptons. The latter has excellent statistical accuracy in the low energy region, crucial for

the $g - 2$, but suffers from systematic theoretical uncertainties in the translation into $g - 2$. The Standard Model prediction based on the τ data tends to be higher by about 150×10^{-11} than that based on e^+e^- , and agrees much better with the measurement. It is important to understand the reason of the difference between e^+e^- and τ data, keeping in mind that the analysis of e^+e^- is also not entirely free from systematic uncertainties. It now appears³⁵ that not all isospin breaking corrections have been applied to the τ data.

At this meeting, Achim Denig presented new experimental results from KLOE, that determine the low energy $e^+e^- \rightarrow$ hadrons annihilation cross-section using radiative return. Those data support direct e^+e^- annihilation measurements, and strengthen the case for a revision of the analysis based on τ decays.

4.3 The NuTeV puzzle

Another recent experimental result disagreeing with the Standard Model is the measurement of the weak mixing angle, $\sin^2 \theta_W$, in muon neutrino and anti-neutrino scattering on an iron target, by the NuTeV Collaboration.³⁶ We have heard two talks on the QCD aspects of this discrepancy, from experimental³⁷ and theoretical perspectives.³⁸ The main focus of those studies is the possible asymmetry in the energy carried by virtual strange quarks and anti-quarks in the nucleons.

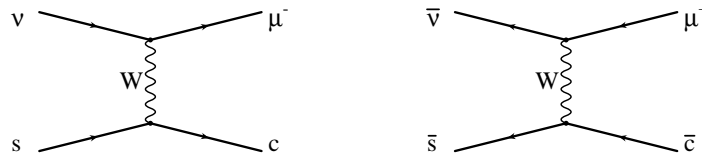


Figure 2: Higher average energy of strange sea quarks compared to anti-quarks enhances the charged current interactions of neutrinos, relative to those of anti-neutrinos.

It is easy to understand how such asymmetry may influence the $\sin^2 \theta_W$ determination. Consider the Paschos-Wolfenstein ratio³⁹ (it is related, but not identical, to the cross-section ratios measured by NuTeV),

$$R^- \equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} = \frac{1}{2} - \sin^2 \theta_W. \quad (3)$$

Suppose now that, for some reason, strange quarks carry, on average, a larger fraction of the nucleon momentum than do strange antiquarks (see Fig. 2). Since the (anti)neutrino scattering cross-section grows with the center of mass energy, such asymmetry increases the denominator in eq. (3) and decreases R^- . This decrease may be wrongly attributed to a too large value of $\sin^2 \theta_W$, if the strange sea asymmetry is present but neglected.

Unfortunately, it is not yet clear whether this asymmetry is present, and whether its magnitude and sign can help explain the NuTeV puzzle. An analysis of dimuon production, carried out by the NuTeV collaboration, suggests that the asymmetry is very small (consistent with zero), and with a tendency towards negative values, that would even slightly increase the discrepancy between the extracted value of $\sin^2 \theta_W$ and the Standard Model prediction. On the other hand, a study by the CTEQ collaboration found a positive asymmetry that can reduce the discrepancy. It is fortunate that CTEQ and NuTeV collaborate to clarify this issue.

4.4 Other topics

Other important topics concerning light hadrons were also discussed. Description of high energy forward hadronic scattering was reviewed⁴⁰ and a discrepancy with previous studies was pointed

out. Multiplicity distributions in proton-(anti)proton and electron-positron collisions were described.⁴¹ A very interesting analogy was suggested between moments of those distributions and virial coefficients in statistical mechanics, whose behavior is related to phase transitions. Those results were illustrated with examples using the Dual Parton Model and the Quark Gluon String Model, also discussed in the context of production and decays of charmed baryons.⁴² Also, investigations of the QED Compton process in electron-proton collisions were reported.⁴³ All these studies presented predictions testable at future experiments, LHC and eRHIC.

5 Renaissance of the charm spectroscopy

An exciting series of discoveries of charmed hadrons has begun shortly after the previous Moriond meeting. Here I will focus on the narrow D_{sJ} states, of which the first $D_{sJ}(2317)$ was reported by BaBar in April 2003, followed by confirmations by other groups, and a discovery of $D_{sJ}(2460)$ by CLEO. A number of interpretations have been put forward to explain the narrow widths of those particles, including baryonia, tetraquarks, etc.

At this meeting we heard a talk by Maciej Nowak, who with Rho and Zahed^{44,45} had predicted the existence of so-called chiral doublers of heavy quark hadrons about ten years prior to those discoveries. Such prediction was also made shortly afterwards by Bardeen and Hill.⁴⁶ It is very tempting to interpret the new states as a confirmation of that prediction. The chiral doubler picture is especially attractive in that it predicts masses of further states and can be tested by ongoing experiments.

To understand the idea underlying chiral doublers, consider symmetries of the hadronic spectrum of states containing a heavy quark. One such symmetry is due to suppression of the chromomagnetic interactions of the heavy quark and is known as the Isgur-Wise or spin-flavor symmetry.⁴⁷ One of its manifestations is the small splitting between masses of mesons such as D and D^* , B and B^* , or, of particular present interest, D_s and D_s^* ; that is, between the ground state 0^- and its hyperfine excitation 1^- . This splitting vanishes as the mass of the heavy quark tends to infinity.

The spectrum feature predicted in the chiral doubler picture is due to the chiral symmetry. Each hadron containing a heavy quark is supposed to have a partner (doubler) differing only by parity. Now, the mass splitting does not vanish in the large mass limit, because the chiral symmetry is broken (the splitting, like constituent quark masses, is primarily due to the spontaneous breakdown of the chiral symmetry). In the infinitely heavy quark limit, the splitting between say a D_s meson and its doubler is the same as that between D_s^* and its doubler. Thus, the chiral doubler picture is very predictive in the B_s system, yet to be fully explored experimentally. (Heavy mesons containing light quarks u, d instead of s also have chiral doublers, but they are generally broader, since they can decay by emitting a pion.)

Within the chiral doubler picture, the quantum numbers of the lowest-lying D_s mesons are assigned as shown in Fig. 3. The established states $D_s(1968)$ and $D_s^*(2112)$ correspond to the left-hand side of that picture, respectively to 0^- and 1^- , and are connected by the heavy quark symmetry. The recent BaBar and CLEO states are interpreted as their chiral doublers, $\tilde{D}_s(2317)$ and $\tilde{D}_s^*(2460)$, and placed on that figure as 0^+ and 1^+ . The tilde denotes chiral partners.⁴⁴ Note that the horizontal sides of this quadrangle are identical within error bars,⁴⁸

$$\begin{aligned} m_{0^+} - m_{0^-} = m_{\tilde{D}_s} - m_{D_s} &= 349.1(1.0) \text{ MeV}, \\ m_{1^+} - m_{1^-} = m_{\tilde{D}_s^*} - m_{D_s^*} &= 347.2(1.5) \text{ MeV}. \end{aligned} \quad (4)$$

The magnitude of these splittings is on the order of the chiral symmetry breaking parameters. Their equality was predicted in the chiral doubler picture.⁴⁵ The numerical value is very close to the prediction of 338 MeV.⁴⁶

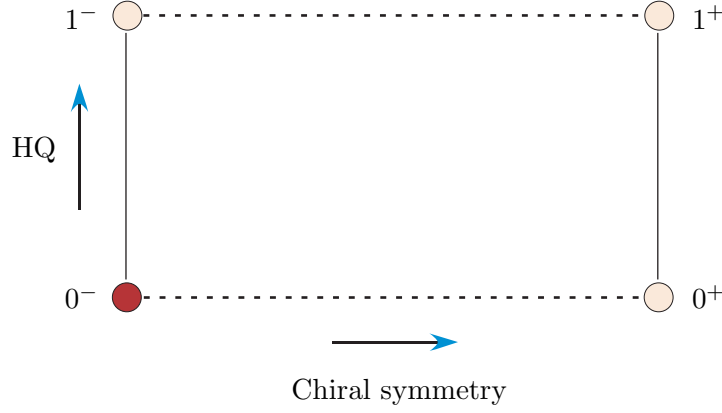


Figure 3: Two symmetries for hadrons containing a heavy quark and light quarks: Isgur-Wise or heavy quark (HQ) spin-flavor symmetry (vertical) and chiral symmetry (horizontal). Labels denote spin and parity of the states, with the 0^- being the ground state (dark circle).

It is now very interesting to consider angular excitations of the light quark. At the time of this Moriond QCD, there were two well established states $D_{s1}(2536)$ (1^+) and $D_{s2}(2573)$ (consistent with 2^+). The existence of their chiral partners was predicted,^{49,50} within a smaller mass difference than the ground state splittings in eq. (4),

$$m_{\tilde{D}_{s1}} = 2721(10) \text{ MeV}, \quad m_{\tilde{D}_{s2}} = 2758(10) \text{ MeV}, \quad (2003 \text{ prediction})^{49} \quad (5)$$

Very recently (three months after the 2004 Moriond QCD), another charm-strange meson $D_{sJ}^+(2632)$ has been discovered by the charm hadroproduction experiment SELEX at Fermilab.⁵¹ It has already been subject of several theoretical interpretations, and may provide the ultimate test of the chiral doubler picture, particularly that it is now possible to make a very precise prediction for another state.

If the SELEX discovery is confirmed, it would fit the chiral doubler scenario as \tilde{D}_{s1} (with the chiral splitting between D_{s1} and \tilde{D}_{s1} even smaller than the prediction, eq. (5)).^{49,50} If we assume that the finite heavy quark mass corrections are similarly small as in the ground state sector, see eq. (4), there should exist another state, with the mass

$$m_{\tilde{D}_{s2}} = 2670(3) \text{ MeV}. \quad (6)$$

The emerging picture of the charm-strange mesons would resemble a Mayan pyramid, as shown in Fig. 4. The horizontal distances between linked states are supposed to represent their mass differences.

It is interesting to contrast the chiral doubler prediction with other interpretations of the latest discovery $D_{sJ}(2632)$. One such interpretation is that it is an S-wave diquark-antidiquark scalar.^{52,53} Explicitly, it would be $[cd][\bar{d}\bar{s}]$ state, that would likely be accompanied by a nearby charge +2 state,⁵² $[cu][\bar{d}\bar{s}]$. This is a clear, testable difference with the chiral doubler picture, where the prediction is for another state of equal charge, +1.

Another interpretation suggests that $D_{sJ}(2632)$ is a radial excitation of the $D_s^*(2112)$.^{54,55} That would be an S-wave 1^- state. If $D_{sJ}(2632)$ is a chiral doubler of D_{s1} , the light quark is predominantly in a D wave (it is a pure D wave in the limit $m_c \rightarrow \infty$).

The outstanding challenges for the chiral doubler approach, if confirmed by a discovery of \tilde{D}_{s2} , is to explain why the chiral shifts of the excited mesons are so small, and to explain the unusual decay pattern of the \tilde{D}_{s1} found by SELEX.⁵¹

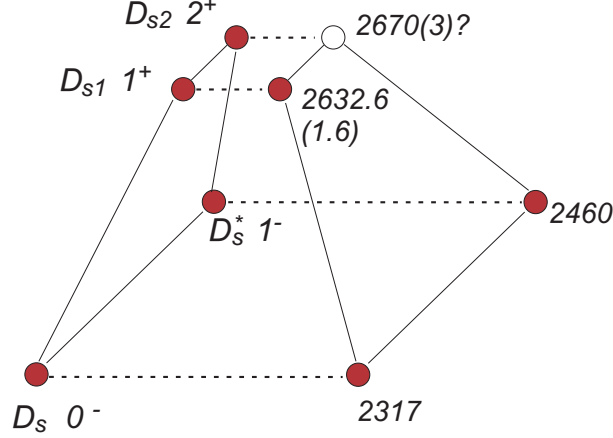


Figure 4: The chiral doubler picture of charm-strange mesons as a Mayan pyramid. The base consists of states connected to the ground state by heavy quark and chiral symmetries, as shown in Fig. 3. The upper level corresponds to the angular excitations of the light quark. The left hand side of that level is well established. The state $D_{sJ}(2632)$ (also called here \tilde{D}_{s1}) has been discovered most recently. The open circle is the predicted state \tilde{D}_{s2} .

6 Production and decay of beauty

Over several years, theoretical predictions disagreed with measurements of b quark production in hadronic collisions. Next-to-leading (NLO) QCD calculations seemed to significantly underestimate the inclusive cross section, by as much as a factor of three. This was puzzling, since inclusive observables at high energy scales are expected to be reliably described by perturbative QCD. Recently, this problem has been solved by a confluence of theoretical and experimental developments.^{56,57}

Part of the solution was the availability of “unprocessed” data, from measurements by the CDF collaboration. Those results were expressed in terms of real hadronic final states (B mesons), avoiding as much as possible extrapolations and deconvolution, that might have introduced biases from simulations. This allowed the theorists to employ b quark fragmentation functions in a fully controlled manner, in connection with an NLO QCD calculation, including mass dependence, and supplemented by a resummation of logarithms of the transverse momentum to mass ratio. The fragmentation functions (a non-perturbative input) were obtained from e^+e^- annihilation data for the b production. Another part of the solution was that the disagreement between theory and experiment turned out to have been somewhat exaggerated, because theoretical uncertainties were not fully appreciated or accounted for in comparisons.

A lesson⁵⁷ drawn from this long story of perceived disagreements is that it is helpful if experiments publish physical observables, perhaps in addition to deconvoluted numbers expressed in terms of quarks. Such approach, giving theorists unambiguous quantities to make comparisons with, may help clarify remaining discrepancies in heavy quark production in electron-proton and photon-photon collisions.

Theoretical progress was also reported in hadronic^{58,59} and semileptonic⁶⁰ decays of B mesons. In hadronic decays $B \rightarrow DM$ and $B \rightarrow D^*M$, with M denoting a light meson, a perturbative QCD formalism was employed to determine factorizable and non-factorizable amplitudes, including strong phases. Predictions are now available for $M = \rho, \omega$ and can be tested by measurements at B factories.^{58,59}

In semileptonic decays, a very impressive recent achievement is the extraction of several heavy quark/meson parameters from moments of lepton energy and hadronic mass. Both the theoretical and experimental efforts that were essential to this end were reported at this

meeting.^{60,61} On the theory side, a new analysis removed the previous disagreement between predicted and measured dependence of the hadron mass moments on the lepton energy cut.

7 Outlook

Thanks to the numerous recent experimental results, QCD and hadronic interactions are again a fascinating research area. If there is a common theme to the news from the diverse fields, from heavy ion collisions, to light baryon spectroscopy, to heavy quark hadrons, I believe it is the insight into the non-trivial structure of the QCD vacuum. Are we seeing the effects of the spontaneous chiral symmetry breaking in the new narrow charm-strange mesons? Do exotic light states, predicted by the chiral soliton model, really exist? Is the deconfining phase transition being seen in heavy ion collisions? These are exciting questions that may soon be definitively answered. There is a flow of new experimental results which challenge theorists' insight and creativity. There are also theoretical predictions that will be confronted by forthcoming measurements. The next Moriond meeting promises to be very interesting, just like this one.

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